Authors' Response to Reviewer Comments – Round 2

Manuscript wes-2026-31

Gräfe et al.

Manuscript: Gräfe et al., *Review and quantification of major risks in wind farm development and operation*, Wind Energy Science

We thank both reviewers for their careful reading and constructive comments. All comments have been addressed; the changes are described below.

Reviewer 1

General comments

> The study presents how different certain risk factors influence financial metrics for wind farm development. The manuscript is well structured, and the results are presented in a understandable matter. The expert elicitation, case study, and suggested risk mitigation provide a holistic contribution. One aspect remains unclear to me. Is this analysis being not possible with other tools or the integration of the different risk factors are new. Are there similar frameworks that could perform the risk analysis? This point could be addressed stronger. Overall, the comments from reviewers 1 and 2 have been addressed in a satisfactory manner.
> The manuscript is very detailed and might be difficult to follow all aspects. Please align the impact assessments between the different risk factors to increase comparability and make the reader more familiar with the single results. Most cases show NPV, LOCE and OPEX. Please add those figures in every case.

Response (framework comparison): We have added a positioning paragraph in Section 2.1 clarifying the relation to existing tools and the nature of the contribution: *"Several established tools address individual parts of this assessment chain, such as stochastic O&M simulation (e.g. WOMBAT, Hammond and Cooperman, 2022), bottom-up cost modeling (e.g. ORBIT, Nunemaker et al., 2020), and integrated design-to-cost frameworks (e.g. WISDEM, NREL). These tools quantify uncertainty within their respective domains. The feature of the analysis presented here is not any individual module, but the consistent propagation of risk categories through a single model chain to project-level financial metrics, enabling comparisons and combined-risk experiments."*

Response (figure alignment): All quantified risk categories now consistently report NPV and LCOE distributions, complemented by the specific metrics each experiment actually varies (CAPEX for supply chain, lost energy for curtailment, OPEX and availability for reliability and O&M processes). In particular, the O&M process section now shows the same three-panel NPV/LCOE/OPEX layout as the reliability section. For the remaining categories, OPEX is held at baseline by design.

Specific comments

R1 – Lines 94–109 (subsection placement)

> Line 94-109: This subsection comes unexpected and might be better placed at the beginning of Section 4. No other upcoming section is discussed here.

Response: We agree and have moved the subsection "Wind farm definition & scenario definition" (study-case table, lifecycle phase figure, and scenario/Monte Carlo setup) from the methodology section to the beginning of Section 4 ("Review and quantification"), where its content is used. It is now Section 4.1 "Wind farm and scenario definition", and the risk category subsections follow as 4.2–4.7.

R1 – Table 1 (dataset availability)

> Table 1: Is there a full dataset available for anyone to recreate the results that are presented in the paper? The provided data in the table would not be enough to calculate NPV etc.

Response: Yes. The complete input configurations required to recreate all results – the baseline wind farm definition (including the full CAPEX and OPEX parameterization, financing terms, and reliability inputs) and all scenario parameter sets – are included in the public WINPACT repository together with the experiment implementation. Table 1 is intended only as a headline summary of the study case. We have extended the code availability statement to make this explicit: *"The WINPACT toolchain, including the experiment implementation and the complete input configurations (baseline wind farm definition and all scenario parameter sets) used in this study, is available under:* `https://gitlab.windenergy.dtu.dk/HiperSim/winpact`*."*

R1 – Line 114 (number of responses)

> Line 114: Could you be exact about the number of responses?

Response: We had an inconsistency in our manuscript. There are 59 valid responses. The manuscript now states this number exactly, the survey figure captions report the per-question selection counts (177 selections from 53 respondents for operational projects; 185 from 51 for future projects; 202 from 53 for research priorities). We have additionally added a sentence clarifying the scope of the survey: *"Given the sample size and the workshop-based collection setting, the survey does not claim statistical representativeness; the results should be read as a directional picture of risk perceptions within a group of experts active in wind energy industry and research."*

R1 – Lines 119–120 (weighting and absolute values)

> Line 119-120: Are there weights assigned if a response included less than three replies? Could you add absolute values too?

Response: No weights are assigned. Each selection counts as one vote, and the reported percentages are shares of all selections cast per question; participants who selected fewer options accordingly contribute fewer votes. We have made this explicit in Section 3.1: *"No weighting is applied: each selection counts as one vote, and the reported percentages are shares of all selections cast per question. Participants who selected fewer options accordingly contribute fewer votes; the polling tool did not strictly enforce the three-selection limit, so some responses contain more."* Absolute values have been added to the survey figure captions ($n = 177$ selections from 53 respondents; $n = 185$ from 51; $n = 202$ from 53).

R1 – Figure 3 (pie chart titles)

> Figure 3: Add titles for the pie charts for fast navigation

Response: Panel titles have been added directly above the pie charts: "(a) Operational wind energy projects" and "(b) Future wind energy projects". The figure caption has been simplified accordingly, as the panels are now self-identifying.

R1 – Table 2 (type definition)

> Table 2: Type is not defined in the table caption. Other tables e.g. Table 4 have a short description of the type

Response: We have added the uncertainty type definitions to the caption of Table 2, consistent with the other uncertainty dimension tables: "A: Aleatory, E: Epistemic, R: Regime."

R1 – Line 248 (Merton jump-diffusion model)

> Line 248: A Merton jump diffusion model might be unknown to the reader. Please provide more information about the purpose of the model or a source for further information

Response: We have expanded the description of the Merton jump-diffusion model to explain its purpose and added a reference to the original publication (Merton, 1976). The revised text reads: *"We fit these parameters using a Merton jump-diffusion model (Merton, 1976), which augments geometric Brownian motion with a compound Poisson jump process to capture sudden price shocks. This is necessary because the frequency of short-term shocks to commodity prices produces heavy tails in the log returns that are poorly captured by Gaussian models."*

R1 – Lines 257–262 (WACC derivation)

> Line 257-262: How are the dept premium converted to WACC? The transition from the mentioned values to chosen values in Table 3 is not clear.

Response: We have added an explicit worked example showing how the WACC values in Table 3 are derived: *"WACC is then obtained from the after-tax weighted average of these rates; for example, the moderate-risk scenario combines a debt rate of 4.43 % (2.7 % risk-free + 1.73 % premium) and a cost of equity of 9.43 % with a 70/30 debt-equity split and a 25 % tax rate, yielding the 5.2 % reported in Table 3."* The other scenario values follow analogously from the respective debt premiums.

R1 – All figures (font sizes)

> All figures: Please align font size between text and figures in the final print for maximal readability

Response: Figure font sizes have been adapted where possible. The simulation result figures now share a common font specification and are included at a uniform width.

R1 – Figure 8 (colour of yearly panel)

> Figure 8: Make the right side for the yearly plot a single colour to avoid misunderstanding that this belongs to the countries.

Response: We thank the reviewer for this suggestion. The figure has not been recreated; instead, we have added a clarification to the caption stating that the colours of the two panels are unrelated.

R1 – Line 381 (curtailment and fatigue loads)

> Line 381: Curtailed operation of turbines could change loads (fatigue) significantly

Response: The reviewer raises a valid point. We have added an acknowledgment in the curtailment review: *"Curtailed operation can also alter the turbine loading regime, which can influence fatigue life. This structural interaction is not considered in the present assessment."*

R1 – Line 540 (which models)

> Line 540: "sensor degradation over time if models are not actively maintained", which models are referenced here?

Response: We have clarified that the "models" refer to the condition monitoring and diagnostic models introduced at the beginning of the paragraph, and corrected the causal logic. The revised clause reads: *"and sensor degradation over time, which erodes diagnostic accuracy unless the condition monitoring and diagnostic models are actively recalibrated."*

R1 – Line 577 (sentence structure)

> Line 577: The sentence has a confusing structure.

Response: The sentence has been restructured. It previously read: *"The aim is to quantify how operational processes, rather than failure behavior, drive availability, OPEX and thus the economic project performance."* It now reads: *"The aim is to quantify the influence of operational processes on availability and OPEX, and thus on economic project performance, independently of component failure behavior."*

R1 – Line 674 (visualizing additivity and super-additivity)

> Line 674: Can the observation that the mean values are additive and tail risk is super additive be visually presented to the reader?

Response: Yes – panel (c) of the combined-risk figure now includes a reference bar showing the range expected under independence (additive mean, quadrature-summed P10–P90 bands) directly below the Combined bar.

R1 – Line 676 (define super-additive)

> Line 676: Please define super-additive

Response: We have added an inline definition at first use: *"However, tail risk is super-additive, i.e. the combined spread exceeds the sum of the individual contributions: the combined P10–P90 band (867 M€) exceeds the quadrature-sum expectation under independence (696 M€) by 170 M€, or ∼24 %."* The numerical comparison that follows serves as a concrete illustration of the definition.

R1 – Section 6 (placement)

> Section 6 feels like a description of modelling/implementation gaps of the used framework. I would have expected this part in the methodology section and not after the results and discussion. I feel like this section could be included in Section 2, since it is not a finding of the case study.

Response: We understand the reviewer's reading, but we would prefer to keep the section in its current position. The integration deficits were not defined beforehand as part of the methodology; they emerged from the reviews and impact assessments, and the combined-risk experiment provides the empirical motivation (super-additive tail risk under fragmented treatment). Placing them in Section 2 would present these conclusions before the supporting evidence. To make this reasoning explicit for the reader, we have added two clarifying sentences at the opening of Section 6: *"The integration deficits discussed in this section are not a priori modeling choices but emerged from the preceding assessments. Although identified here in the context of WINPACT, they are formulated as general requirements for integrated risk assessment rather than as deficiencies of a specific tool."*

Reviewer 2

General comments

Thank you to the editorial team and the authors for the opportunity to review. This paper presents a general status and quantification of risks in the wind industry. It does so for offshore and onshore projects and does a good job collecting the available information into a coherent overview. At its core, the paper has a good message for both academics and people in industry that presents a clear perspective on these project risks.
After review, the verbosity has been tuned to enhance the presentation of the study. It could improve with some additional synthesizing. This redundant verbosity is most apparent in the risk descriptions in the key uncertainty dimensions tables. The traceability of the reasoning could be enhanced by having the quantified risks, that are presented in the figures or other frequently used metric (e.g., increased OPEX and CAPEX), be the same as the ones described in the tables. This could reduce the leap of the qualitative analysis to the quantitative analysis. Table 2 is the best example of a traceable table.
The chapter 'Long-term asset viability - Through-life decision making' ends with three outcomes where the only distinguishing factor comes from the LTE decision. That presents the chapter as the actual through-life decision making as ineffective. The two ways I could see this be improved are by:

- restructuring of the message of the chapter to focus on the end-of-life decision,
- extending the discussion and results that reflect No-LTE for different operational strategies. With for instance, the work described in N. Requate et al., 2023.

Response (table verbosity and traceability): We have revised the "Risk" column of all five key uncertainty dimension tables (through-life, curtailment, reliability, O&M inefficiencies, and upscaling) so that each entry leads with the quantified metrics used in the impact assessments and result figures (CAPEX, OPEX, AEP, availability, downtime, revenue, NPV), retaining the causal mechanism only where it adds information. This shortens the table entries and establishes a consistent vocabulary between the qualitative tables and the quantitative results, following the pattern of Table 2.

Response (through-life chapter): We have followed the reviewer's first suggestion and restructured the message of the chapter to focus on the end-of-life decision. The subsection is now titled "Long-term asset viability – End-of-life decision making", and the framing throughout the review, impact assessment, and synthesis has been aligned: the broader lifecycle uncertainties are presented as inputs that culminate in the end-of-life decision, which the quantitative assessment then addresses through the lifetime extension scenarios. Extending the results with No-LTE variants under different operational strategies, as in Requate et al. (2023), would require a formalized coupling between operational strategy, loads, and reliability – precisely the interface gap identified in Section 6 – and is therefore beyond the scope of this study. We have, however, added

this direction explicitly to the future-work statement closing the impact assessment: *"future work should therefore address the end-of-life decision under the combined uncertainty dimensions summarized in Table 4, as well as load-managed operational strategies that actively shape the damage budget available for extended operation (Requate et al., 2023)."*

Specific comments

R2-1 (Figure 1 capacity)

> Figure 1's capacity does not correspond to the capacity in the table below. Figure 1 shows 880MW, while the table shows 748MW.

Response: Thank you for spotting this inconsistency. The figure has been corrected to show 748 MW, consistent with the study case table.

R2-2 (Figure 1 dotted box)

> Figure 1's box with dotted line is not explained in a legend and has no description elsewhere. Does it need to be dotted?

Response: The dotted style carried no intended meaning. The box has been changed to a solid line, consistent with the other elements of the diagram.

R2-3 (α not defined)

> α has not been defined in the text and it is not clear what its meaning is from the table. An in-text description before it appears would solve that.

Response: We have added an explicit in-text definition of the multiplier notation before Table 3: *"The multipliers α_s^{μ}, α_s^{σ}, and α_s^{λ} scale the historical drift, volatility, and jump intensity of the commodity price processes, respectively; $\alpha = 1$ recovers the historical estimate, while values below or above one dampen or amplify the corresponding parameter."*

R2-4 (LCOE and bankability)

> Higher LCOE and reduced bankability in the same risk is ineffective. LCOE increased because of lower bankability.

Response: The reviewer is correct that reduced bankability and higher LCOE are causally linked rather than independent effects. We have revised the risk column to make the causal chain explicit: "Reduced bankability, leading to higher cost of capital and LCOE."

R2-5 (time horizon of limited infrastructure)

> On P10, I am not sure you want to say, 'development & financing through operation', because the time horizon of limited infrastructure goes before and beyond that with a much wider impact.

Response: The reviewer is correct. Infrastructure constraints (ports, vessels) affect not only development and construction but also major component replacements during operation and, ultimately, decommissioning. We have extended the time horizon to "Development & financing through end-of-life", covering the full lifecycle as defined in the paper.

R2-6 (source for tariff claim)

> P. 10 the following text would improve with a source: "Governments have used industrial policy to create import barriers (i.e. tariffs), limiting the availability of global supply chain components."

Response: We have added two supporting references to this statement: the U.S. DOE Wind Energy Supply Chain Deep Dive Assessment (Baranowski et al., 2022, `https://doi.org/10.2172/1866032`), which examines trade policy measures and import reliance in the wind supply chain, and Shields et al. (2023), which discusses supply chain localization policies.

R2-7 (undefined $\tilde{m}$ in Figures 5 and 6)

> Figures 5 and 6 have a $\tilde{m}$ as variable that I could not find back in the text. Please define or omit it from the figures.

Response: The symbol $\tilde{m}$ denotes the median. We have added definitions for both statistical symbols appearing in the figures to the captions: "μ denotes the mean, $\tilde{m}$ the median."

R2-8 (negative prices and CfDs)

> P.19 touches upon the rise of negative prices. It seems to suggest negative prices because of high-wind penetration markets. However, that seems to be a flawed cause and effect relationship. I believe it is a consequence of the contracts for difference schemes in those countries. So, this should definitely affect the chances to get a CfD, but that is because CfDs are also a part of the problem.

Response: We agree that the original phrasing implied an incomplete causal chain. Oversupply from high VRE production alone would drive prices toward zero, but it is the interaction with production-based support schemes that sustains negative prices. We have revised the paragraph accordingly: *"Market-driven curtailment arises when wholesale electricity prices turn negative during periods of high VRE production. Oversupply alone, however, does not push prices below zero: production-based support schemes such as feed-in premiums and contracts for difference (CfDs) remunerate per unit of energy produced and thereby incentivize generation even at negative prices."*

R2-9 (market-driven curtailment table row)

> On a similar note, as the previous point, please update the Market-driven curtailment row in the table on page 20.

Response: We have updated the Market-driven curtailment row consistently with the revised text. The uncertainty source now reads: "Frequency and duration of negative electricity prices, driven by VRE penetration and production-based support scheme design; demand flexibility and storage deployment." We have additionally added "R" to the uncertainty type, since support scheme evolution constitutes a regime-level uncertainty in the paper's taxonomy.

R2-10 (missing space)

> P37, row 4 of the table E, R misses a space.

Response: Fixed. The spacing has been corrected from "E,R" to "E, R" in the O&M logistics row of the upscaling uncertainty table.

Reference list

Please also fix these errors in the list of references:

- Duplicate DOI prefixes: L765, L775, L780, L790, L805, L810, L830, L835, L860, L870, L885, L900, L905, L925, L930, L940, L960, L965, L970, L975, L985, L990, L1020, L1035, L1040
- Typo errors: L790, L845, L850, L990, L800, L955, L855, L955, L835, L840, L930, L960, L965, L1020
- I believe there should not be a space in these article number: L765, L775, L780, L790, L835, L850, L855, L905, L940, L965, L970, L975, L990, L1005, L1020, L1035
- Please add the full author list: L770, L1010
- Incomplete reference: L805, L995
- Journal missing or incorrect: L930, L965, L970, L1020, L1035
- Placeholder or missing page/article number: L830, L900, L920, L945
- Missing [data set] or [code] tag: L850, L915
- Please add last access date where required

Response: All reference list issues have been addressed:

- **Duplicate DOI prefixes:** The DOI fields of 36 entries contained the full URL (https://doi.org/10.xxxx), which the journal style prefixes again. All DOI fields now contain the bare DOI.
- **Spaces in article numbers:** The article numbers in the bibliography source contain no spaces; the apparent spaces in the rendered reference list were line-breaking artifacts caused by the malformed duplicated DOI links, and are resolved by the DOI correction above. We have verified all page and article-number fields.
- **Typos:** Corrected misspellings and capitalization errors in titles and author names, missing diacritics in several author names, a stray formatting command, and an encoding artifact. Additionally fixed rendering-level errors: unescaped special characters in six journal/title/note fields and Unicode artifacts (curly quotes/apostrophes and non-breaking hyphens) across all bibliography files.
- **Full author lists:** Completed the author lists of van Kuik et al. (2016) (full 27-author list) and Behr et al. (2017) (full 10-author list). Two further entries with malformed author fields (Tapoglou et al., 2025; Pulikollu et al., 2021) were corrected to full, properly formatted lists.
- **Incomplete references:** Completed the placeholder volume/issue/page fields of Fischer et al. (now correctly 2019, 34(7), 6332–6344); retyped and completed the DOE Pathways to Commercial Liftoff and Fuchs et al. (NREL/TP-5000-88988) reports with institution, report number, and URL; added the missing URL to GWEC (2023); removed report-number artifacts from a pages field; removed an empty URL field; corrected a wrong conference note (EERA DeepWind'2017); and fixed non-standard article-number fields so that article numbers render.
- **Duplicates:** Removed four duplicate entries from the bibliography files.
- **Journal missing or incorrect:** Updated Walgern et al. from the discussion preprint to the final published version (Wind Energ. Sci., 11, 1553–1568, 2026);
- **[data set] tags:** Added the "[data set]" designation to the three dataset references (Ember European wholesale electricity price data; NREL 2024 Annual Technology Baseline; EPRI WinNER database).
- **Last access dates:** Added last-access dates to all sixteen web-resource references.